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LOCOMOTIVE CRASH ENERGY MANAGEMENT COUPLING TESTS

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ABSTRACT

Research to develop new technologies for increasing the safety of passengers and crew in rail equipment is being directed by the Federal Railroad Administration's (FRA's) Office of Research, Development, and Technology. Crash energy management (CEM) components which can be integrated into the end structure of a locomotive have been developed: a push-back coupler and a deformable anti-climber. These components are designed to inhibit override in the event of a collision. The results of vehicle-to-vehicle override, where the strong underframe of one vehicle, typically a locomotive, impacts the weaker superstructure of the other vehicle, can be devastating. These components are designed to improve crashworthiness for equipped locomotives in a wide range of potential collisions, including collisions with conventional locomotives, conventional cab cars, and freight equipment.

Concerns have been raised in discussions with industry that push-back couplers may trigger prematurely, and may require replacement due to unintentional activation as a result of service loads. Push-back couplers are designed with trigger loads meant to exceed the expected maximum service loads experienced by conventional couplers. Analytical models are typically used to determine these required trigger loads. Two sets of coupling tests are planned to demonstrate this, one with a conventional locomotive equipped with conventional draft gear and coupler, and another with a conventional locomotive retrofit with a push-back coupler. These tests will allow a performance comparison of a conventional locomotive with a CEM-equipped locomotive during coupling. In addition to the two sets of coupling tests, car-to-car compatibility tests of CEM-equipped locomotives, as well as a train-to-train test are also planned. This arrangement of tests allows for evaluation of the CEM-equipped locomotive performance, as well as comparison of measured with simulated locomotive performance in the car-to-car and train-to-train tests.

The coupling tests of a conventional locomotive have been conducted, the results of which compared favorably with pre-test predictions. In the coupling tests of a CEM-equipped locomotive, the coupling speed for which the push-back coupler (PBC) triggers will be measured. A moving, CEM-equipped locomotive will be coupled to a standing cab car. The coupling speed for the first test will be low, approximately 2 mph. The test will then be repeated with the speed increasing incrementally until the PBC triggers.

This paper describes the fabrication, retrofit, test requirements, and analysis predictions for the CEM coupling tests. The equipment to be tested, track conditions, test procedures, and measurements to be made are described. A model for predicting the longitudinal forces acting on the equipment and couplers has been developed, along with preliminary predictions for the CEM coupling tests.

BACKGROUND

The Office of Research, Development, and Technology of the Federal Railroad Administration (FRA) and the Volpe Center are continuing to evaluate new technologies for increasing the safety of passengers and operators in rail equipment. In recognition of the importance of override prevention in train-to-train collisions in which one of the vehicles is a locomotive [1, 2, 3], and in light of the success of crash energy management technologies in passenger trains [4], FRA seeks to evaluate the effectiveness of components that are integrated into the end structure of a locomotive that are specifically designed to mitigate the effects of a collision and, in particular, to prevent override of one of the lead vehicles onto the other [5].

A research program has been recently conducted that developed, fabricated and tested two crash energy management (CEM) components for the forward end of a locomotive: (1) a deformable anti-climber, and (2) a push-back coupler [6, 7]. Detailed designs for these components were developed, and the performance of each design was evaluated through large deformation dynamic finite element analysis (FEA). Two test articles were fabricated and individually dynamically tested by means of rail car impact into a test wall in order to verify certain performance characteristics of the two components relative to specific requirements. The tests were successful in demonstrating the effectiveness of the two design concepts. Test results were consistent with finite element model predictions in terms of energy absorption capability, force-displacement behavior and modes of deformation.

This research program will eventually integrate the two CEM components onto a locomotive in order to demonstrate that these components work together to mitigate the effects of a collision and prevent override [8]. A series of dynamic CEM coupling tests is planned to demonstrate that the push-back coupler will, or will not, trigger, depending on the proper conditions. However, before demonstrating the robustness of the push-back coupler, it is important to establish a baseline for conventional coupling to determine the maximum non-destructive conventional coupling speed. Therefore, conventional coupling tests were conducted [9], [10]. The coupling tests were conducted repeatedly with the same F40 locomotive and M1 passenger car, starting at 2 mph for the first test, and increasing in increments of 2 mph until damage occurred in either vehicle. The results of these conventional coupling tests compare favorably with pre-test predictions. The lowest coupling speed at which damage occurred was 6 mph. The results of the conventional coupling tests will be compared to the results of the tests described in this paper.

CEM COUPLING TESTS REQUIREMENTS

The CEM coupling tests will be conducted at the Transportation Technology Center (TTC) in Pueblo, Colorado. In preparation, the two CEM components, a deformable anti-climber (DAC), and a push-back coupler (PBC), will be retrofit onto an F40 locomotive. For these tests, the CEM locomotive will impact the stationary M1 at increasing speeds until the PBC fuse triggers. The coupling tests will be conducted repeatedly with the same CEM F40 locomotive and M1 passenger car, starting at 2 mph for the first test, and increasing in speed until the PBC fuse triggers, as shown in Figure 1. For these impact tests, the M1 car will be braked.

The primary objective is to demonstrate the robustness of the PBC design and determine the impact speed at which PBC triggering occurs. The structural performance of the PBC and the coupling vehicles will be measured and characterized under a range of dynamic coupling speeds until triggering occurs. The results of the CEM coupling tests will be compared to the analytical predictions and evaluations made on the performance of the equipment. The results will also be compared to the results of the previously run conventional coupling tests.

The information desired from the CEM coupling tests includes the longitudinal, vertical and lateral accelerations of the equipment and the displacements of the couplers. Information is also sought on the sequence of events, e.g., timing of coupling and then triggering of the PBC fuse. The equipment and components will be inspected carefully after each coupling test to ascertain the condition of the equipment and determine if any damage has occurred.

The force-crush characteristic (i.e., the load that the couplers and supporting structure develop during the coupling procedure) is a key characteristic of the couplers and the cars. One purpose of these tests is to take measurements for comparison with analytical predictions in order to validate that such predictions are accurate. Another comparison that will be made will be with the measurements taken for the CEM coupling tests.

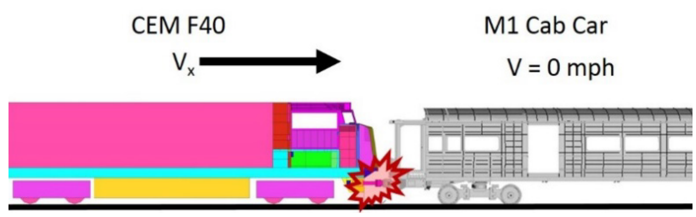

Figure 1. Schematic of coupling test initial conditions.

CEM Locomotive

The equipment that will be used for the CEM coupling test will be a retrofit F40 locomotive and an M1 passenger cab car. Retrofit F40 locomotive #234 will be used in the tests and can be seen in Figure 2.

Figure 2. F40 locomotive #234 will be used in the conventional coupling tests.

The computer model of the CEM retrofit F40 locomotive design is shown in Figure 3. The DAC is retrofit in-line with the anti-climber and underframe of the locomotive. Figure 4 shows a bottom view of the CEM draft pocket and rear end of the PBC. The PBC is held by the sliding lug, which is attached to the draft pocket with shear bolts. During an impact that occurs at greater than coupling speeds, the PBC is triggered. Once the fuse is triggered, the PBC absorbs energy as it pushes back. When the PBC stroke is exhausted, the shear bolts are broken by the mounting impact force. This causes the sliding lug to slide back. At this point, the load path transfers from the PBC to the DAC, which crushes in a controlled manner while absorbing more collision energy. The entire CEM system is designed to have the impacting vehicle ends engage while absorbing the energy of the collision. The design development and requirements of the CEM components are detailed in previous papers [5], [6], [7].

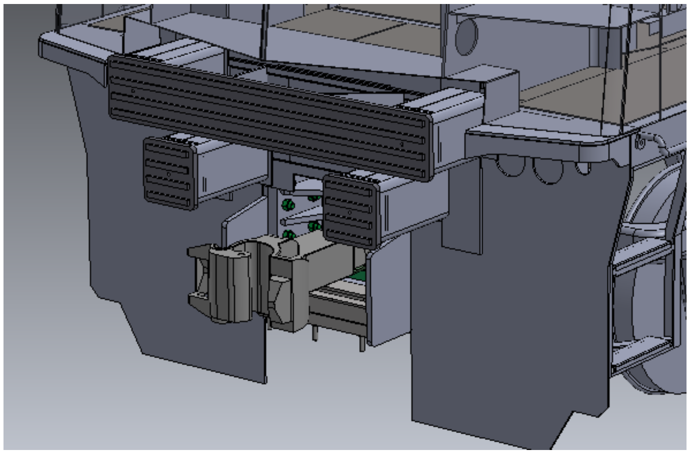

Figure 3. CEM retrofit locomotive design.

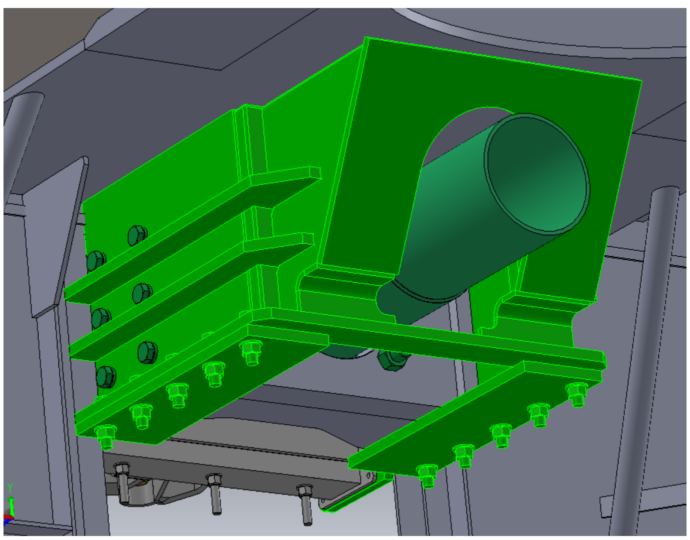

Figure 4. PBC design.

The conventional F40 locomotive was retrofit with the CEM system (DAC and PBC) onto its front end. This included removal of the draft pocket, then fabrication and assembly of the complete CEM system and its attachments to the locomotive. Figure 5 shows the locomotive with the original coupler and draft pocket removed. In Figure 6, the locomotive is being prepared to accept the retrofit of the DAC on the front, as well as the CEM draft pocket, sliding lug, and PBC. A photo of the CEM draft pocket being assembled is shown in Figure 7, and a photo of the sliding lug being assembled is shown in Figure 8.

Figure 5. Locomotive with draft pocket removed.

Figure 6. Locomotive retrofit in process.

Figure 7. CEM draft pocket assembly.

Figure 8. Sliding lug.

After assembly, the CEM draft pocket was welded onto the locomotive, as shown from the front in Figure 9, and from the side in Figure 10. The sliding lug was then placed inside the CEM draft pocket (Figure 11).

Figure 9. Installation of CEM draft pocket.

Figure 10. CEM draft pocket attachment.

Figure 11. CEM draft pocket and sliding lug installation.

The action of the sliding lug was tested several times to ensure that it moved through its range of motion within the draft pocket without binding. Figure 12 shows the sliding lug in the front position, and Figure 13 shows it in its back position.

Figure 12. Sliding lug inside CEM draft pocket, front position.

Figure 13. Sliding lug inside CEM draft pocket, back position.

The DAC bottom crush tubes are shown in Figure 14, and the top plate and one of the top crush tubes is shown in Figure 15.

Figure 14. DAC bottom crush tubes.

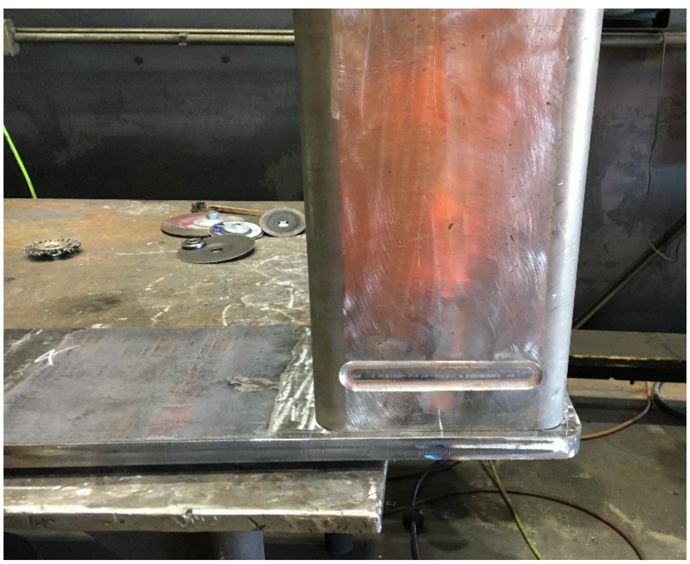

Figure 15. DAC top plate and crush tube.

The PBC coupler will be installed within the sliding lug, then the DAC assembly will be installed on the locomotive. As of the submission of this paper, the retrofit of the CEM locomotive was not yet complete.

The tests being conducted are coupling tests. The primary objective is to demonstrate the robustness of the PBC design and determine the impact speed at which PBC triggering occurs. Therefore, it is expected that only the PBC will be loaded, and not the DAC, in these tests. Also, the tests will only be conducted to the point of triggering the PBC, and not to its full stroke.

M1 Cab Car

The M1 cab car that will be used in the CEM coupling tests is M1 #8221, shown in Figure 16.

Figure 16. M1 cab car #8221 with some fire damage.

Figure 17 shows the M1 draft gear and yoke. The draft gear is single acting, so there are two sets of rubber/metal plates. One pack acts in buff and the other acts in draft. These are key elements to be tested in the coupling tests. The load imparted to the cab car underframe is a function of the draft gear stiffness, as well as of the stiffness of the structure that supports the draft gear. Like the locomotive's components, these cab car components will be highly loaded during the test.

Figure 17. M1 draft gear and yoke.

OVERVIEW OF IMPLEMENTATION

Measurements are to be made with accelerometers, strain gages, displacement transducers (string potentiometers), and high speed video cameras. This instrumentation is intended to capture the gross motions of the equipment, the relative motion of the couplers and M1 draft gear, the load paths, the local deformations, and the sequence of events, e.g., coupling, stroking of the M1 draft gear, triggering of the PBC. The coupling speed of the locomotive will be measured with radar and a reflector-based sensor.

Accelerometers

Figure 18 shows a schematic illustration of the accelerometer locations planned for the F40 locomotive carbody and trucks. Additional accelerometers will be located on the PBC and the sliding lug. The accelerometers on the carbody are intended to capture the three dimensional gross motions of the carbody – longitudinal, lateral, vertical accelerations, as well as yaw, pitch, and roll. For each test, the measured longitudinal accelerations will be used to calculate impact forces, as well as the equipment velocities and displacements. Corresponding instrumentation locations are planned for the M1 car.

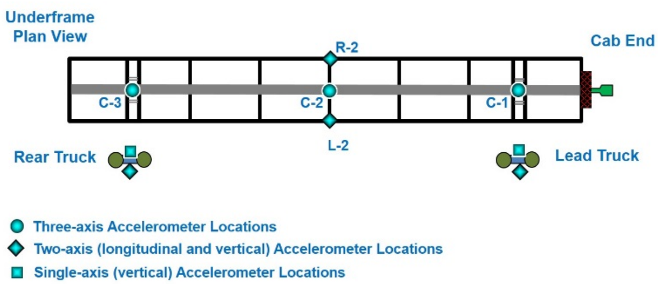

Figure 18. Schematic illustration of M1 cab car accelerometer locations

Figure 19 shows a photograph annotated with the locations for the accelerometers on the PBC. Note that the photograph shows a conventional coupler. The PBC will have an accelerometer on both the right and left sides, and there will also be an accelerometer that will measure longitudinal acceleration. Similarly, the sliding lug will have an accelerometer on both the right and left sides, and there will also be an accelerometer that will measure longitudinal acceleration. Accelerometers are planned for corresponding locations on the M1 coupler.

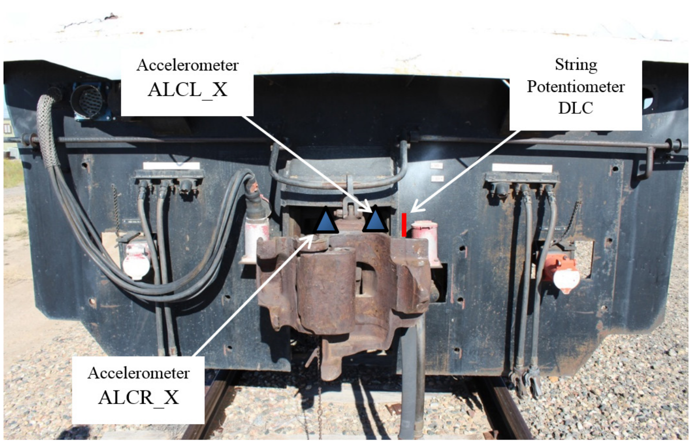

Figure 19. Photograph of locations planned for F40 locomotive coupler longitudinal accelerometers.

Strain Gages

On the locomotive carbody, strain gages will be located on the cant rail, the draft/center sill, and the side sills. On the locomotive PBC assembly, strain gages will be located on the sliding lug, the lug support, and the draft pocket. On the M1 carbody, strain gages will be located on the cant rail, the draft/center sill, and the side sills.

Displacement Transducers

Both the locomotive and the M1 will be fitted with displacement transducers on their secondary suspensions, their couplers, and their underframes. Figure 20 shows a photograph illustrated with the planned locations for some of the displacement transducers on the M1 coupler. Relative vertical, lateral, and longitudinal displacements will be measured. Corresponding measurements will be made of the locomotive coupler. These measurements are intended to capture the longitudinal response of the draft gear/PBC, and any motions that may lead to lateral buckling or override.

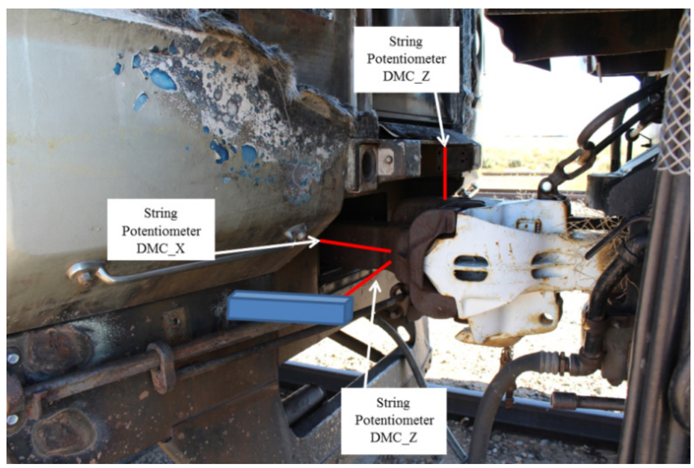

Figure 20. Photograph of locations planned for M1 cab car coupler longitudinal displacement transducers.

Figure 21 shows a photograph illustrated with the planned location for the longitudinal displacement transducer intended to measure potential M1 center sill deformation. A corresponding transducer is planned for the F40, to measure potential deformation of the locomotive draft gear box.

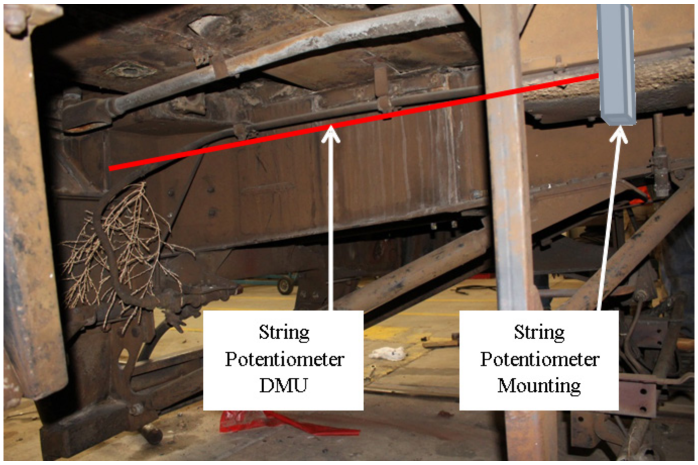

Figure 21. Photograph of locations planned for M1 cab car end structure longitudinal displacement transducers.

In addition to the coupler and underframe transducers, the vertical displacements of the secondary suspension will also be measured for both vehicles. The intent is to capture any pitching motion.

Locomotive Speed Sensors

Redundant speed sensors will measure the impact speed of the locomotive when it is within 20 inches of the impact point. The speed trap is a reflector-based sensor. This technology uses ground-based reflectors separated by a known distance, and a vehicle-based light sensor that triggers as the locomotive passes over the reflectors. The last reflector is within 10 in. of the impact point. The time interval between passing the reflectors is recorded, then the speed is calculated using distance and time. Back-up speed measurement will be made with a hand-held radar gun.

Cameras

Six high frame rate and four conventional frame rate high definition (HD) video cameras will record each impact test conducted. Figure 22 shows a schematic of the camera locations with respect to the vehicles. Final alignment and sighting of the cameras will be done when the locomotive and M1 car are positioned at the impact point prior to the start of test.

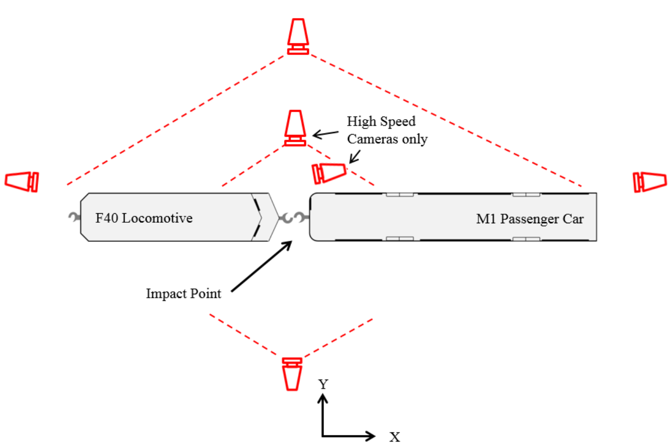

Figure 22. Schematic of camera locations.

Data Acquisition

A set of 8-channel battery-powered on-board data acquisition systems will record data from instrumentation mounted on both the M1 cab car and the F4 locomotive. These systems provide excitation to the instrumentation, analog anti-aliasing filtering of the signals, analog-to-digital conversion, and recording of each data stream.

The data acquisition systems are GMH Engineering Data BRICK Model III units. Data acquisition will comply with the appropriate sections of SAE J211. Data from each channel will be anti-alias filtered at 1735 Hz, then sampled and recorded at 12,800 Hz. Data recorded on the Data BRICKS will be synchronized to time zero at initial impact. The time reference will come from closure of the tape switches on the front of each test vehicles. Each Data BRICK can take shock loading up to at least 100 g. On-board battery power will be provided by GMH Engineering 1.7 Amp-hour 14.4 Volt NiCad Packs. Tape Switches, Inc., model 1201-131-A tape switches will provide event initial contact.

Software on the Data BRICK will be used to determine zero levels and calibration factors rather than relying on set gains and expecting no zero drift. The Data BRICKS will be set to record one second of data before initial impact and seven seconds data after initial impact.

Test Conduct

Speed trials will be conducted to determine the distance needed to roll back the locomotive for each desired impact speed. The weights of the locomotive and M1 will be measured prior to the tests. The tests will be conducted on tangent track with approximately 0.85% grade. Shortly before each test the release distance will be adjusted based on wind speed and direction. Personnel will be positioned with radar guns to obtain back-up speed measurements. The locomotive will be rolled back from the M1 cab car and released.

After each impact test, the stopping distance will be measured. An investigation will be conducted to determine if the PBC has activated or if any damage was done to the deformable anti-climbers. The structural members of both the locomotive and the M1 will also be visually inspected for new damage. If the PBC has not been activated, the test will be repeated with the locomotive release location being adjusted to increase its impact speed to the next desired level. After each test, data will be downloaded to laptop computers from the on-board data acquisition system. Prior to the next test, all string potentiometers will be checked and re-set, if necessary.

SIMPLIFIED ANALYSIS

Figure 23 shows a schematic of a simplified one-dimensional three-degree of freedom dynamic model of the coupling test. The M1 cab car is represented by two masses, one for the carbody and another mass for the trucks. The two trucks are represented by a single mass, with the assumption that they both move simultaneously. This mass was added to the model when the conventional coupling test results showed that the motions of the trucks relative to the carbody could be more than 1 inch, and thus were not negligibly small [10]. The F40 locomotive is represented by a single mass; the conventional coupling test results showed that the carbody and trucks of the locomotive acted essentially as a single mass. The primary purpose of the model is to estimate the peak force acting between the masses as a function of coupling speed.

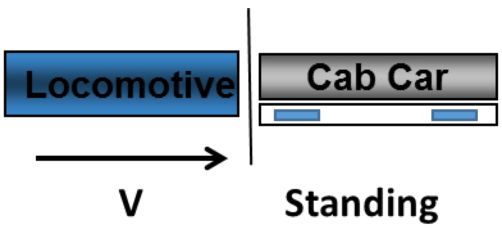

Figure 23. Schematic of one-dimensional two-degree-of-freedom lumped parameter coupling model.

Figure 24 shows the force/displacement characteristics input into the simplified model. The characteristic between the trucks and M1 carbody and the characteristic between the F40 and the M1 carbody are shown. The operational range of the combined F40 and M1 draft gears is about 4 inches. The PBC triggers after approximately 6 inches of displacement between the F40 and the M1 carbody. The bottoming stiffness is between the operational range and the triggering of the PBC. The bottoming stiffness is a function of both the draft gear itself and the support provided to the draft gear by the locomotive and cab car underframes. The slope of this portion of this characteristic has been estimated from the conventional coupling test results [10]. The force/displacement characteristic between the truck and M1 carbody has also been estimated from the conventional coupling test results.

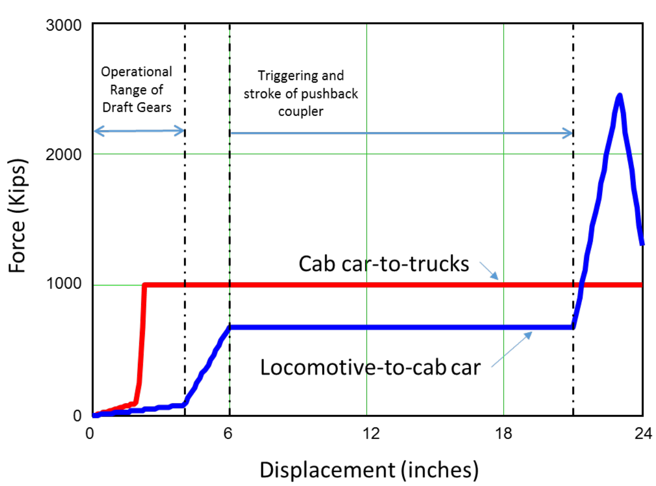

Figure 24. Input force/displacement characteristics for lumped-parameter model.

Figure 25 shows the peak coupling force along the line of draft as a function of coupling speed. The graph is also annotated with the M1 car elastic strength [11]. The coupler load is predicted to exceed the trigger load (674 lb.) for initiation of coupler push-back at just over 7 mph. The truck-to-carbody load for the M1 is predicted to reach 250 kips at a speed just under 5 mph. Therefore, damage to the truck-to-carbody connection is expected for coupling speeds above 5 mph. During the tests, some deformation of the M1 carbody is expected when the PBC triggers; this deformation is not expected from the load along the line of draft, but from the load at the truck attachment. Note that equipment damage and triggering of the PBC are expected to occur at speeds greater than the maximum coupling speed recommended by the Association of American Railroads, 4 mph [12].

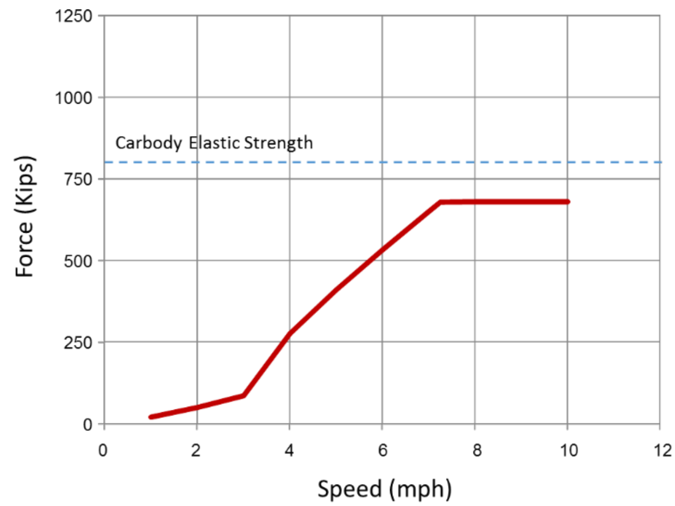

Figure 25. Peak force as a function of coupling speed, results from lumped-parameter model.

SUMMARY

The FRA, with support of the Volpe Center, is conducting research on the implementation of CEM features on locomotives. These features include push-back couplers and deformable anti-climbers. A series of tests are being conducted, including coupling tests, car-to-car impact tests, and a train-to-train collision test. This arrangement of tests allows for comparison of conventional and CEM-equipped locomotive measured performance during coupling. Additionally, this arrangement of tests allows for evaluation of the CEM-equipped locomotive performance, as well as comparison of measured with simulated locomotive performance in the car-to-car and train-to-train tests.

In the coupling tests of CEM equipment, the coupling speed at which the PBC will trigger will be measured. A moving locomotive will be coupled to a standing cab car. The coupling speed for the first test will be 2 mph, and the tests will repeat with the speed increasing incrementally until the PBC triggers. Coupling tests of both conventional and push-back couplers are necessary so that their performance may be compared. Coupling speeds which lead to equipment damage have been determined for conventional couplers. Coupling speeds which cause the PBC to trigger will be tested. The results of these tests will be compared.

This paper describes the test requirements and analysis predictions for the coupling tests of CEM equipment. The equipment to be tested, vehicle retrofit and preparation, track conditions, test procedures, and measurements to be taken are described. A one-dimensional model for predicting the longitudinal forces acting on the equipment and couplers has been developed, along with preliminary predictions for the CEM coupling tests. The PBC load is predicted to exceed the trigger load for initiation of coupler push-back at just over 7 mph.

The CEM coupler test is being carried out, as this paper is being written. Planning is underway for the car-to-car impact tests, and a train-to-train collision test. Additional papers are planned as additional tests are conducted.

NEXT STEPS

Additional full-scale dynamic tests are planned which will accomplish the objectives of demonstrating that the locomotive CEM system performs well in service, provides crashworthiness compatibility with a range of equipment, and exhibits increased crashworthiness over conventional equipment. The planned tests are based on a head-on collision scenario in which a locomotive-led train collides with a stationary train. The stationary train can be led by a conventional locomotive, a CEM locomotive, a cab car, or a freight car. The overall objective of these tests is to demonstrate the effectiveness of the locomotive CEM system, comprised of a PBC and a DAC. The first set of tests were coupling tests of a conventional F40 coupling with an M1. The second set of tests, described in this paper, will be coupling tests of an F40 retrofit with a PBC coupling with an M1 cab car. This arrangement of the tests allows comparison of the conventional coupler performance with the performance of the PBC. The third set of tests will be vehicle-to-vehicle impact tests of a CEM F40 (retrofit with a PBC and a DAC) impacting a stationary vehicle. The final set of tests are planned to be train-to-train impact tests of a CEM F40-led train impacting a conventional stationary train.

Table 1 summarizes the critical measurements for each of the four types of tests. The first two sets of tests, the coupling tests, will demonstrate that the PBC performs as expected in service. The vehicle-to-vehicle tests will demonstrate that the components work together as an integrated system to provide crashworthiness with a range of equipment, and the train-to-train tests will demonstrate the effectiveness of the crashworthy components.

While the overall objective of these tests is to demonstrate the effectiveness of locomotive crashworthiness equipment, the test data will also be used for comparison with analyses and modeling results. The measurements will be used to refine the analysis approaches and models and assure that the factors that influence the response of the equipment are taken into account. Table 1 lists the measurements that are critical in assuring the appropriate modeling and analysis of the equipment.

Efforts are underway to prepare for the second series of tests, the CEM coupling tests (highlighted in blue in Table 1), described in this paper. An F40 very similar to the one used in the conventional coupling tests is being prepared for retrofit of the crashworthy components. The PBC and DAC are being fabricated for retrofit. An M1 cab car is also being prepared for the tests. The CEM coupling tests are planned for early 2017.

Table 1. Test descriptions and critical measurements

Test Description	Critical Measurements
Conventional Coupling Tests	• Maximum non-destructive coupling speed • Dynamic impact forces • Impact accelerations • Displacements
CEM Coupling Tests	• Maximum non-destructive coupling speed • Dynamic crush forces • Impact accelerations • Displacements • Effectiveness of PBC
Vehicle-To-Vehicle Tests	• Dynamic crush forces • Accelerations • Displacements • Effectiveness of PBC and DAC working as a system
Train-To-Train Tests	• Effectiveness of crashworthy components at managing load path • Effectiveness of crashworthy components in inhibiting override and lateral buckling

ACKNOWLEDGEMENTS

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